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# The Kinematics of Dwarf Spheroidal Galaxies

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**Abstract:** I review observational data on the kinematic properties of dwarf spheroidal galaxies in the halo of the Milky Way and beyond. The present data confirm previous claims that these small galaxies have unusually large central velocity dispersions. 'Simple' sources of bias such as binary stars, internal atmospheric motions, measurement errors and small sample sizes cannot explain the large dispersions measured in all dSph systems. Recent data suggest that in some of these dwarfs the velocity dispersion profiles are flat out to their classical tidal radii. I discuss how these results can (or cannot) be understood by invoking a variety of distinct models, including classical dark matter halos, tidal disruption, and MOND.

## 1. Introduction

Dwarf spheroidal (dSph) galaxies have provided a host of surprises ever since their 'renaissance' in the early 1980's. Led early on by Marc Aaronson, it has become increasingly obvious that these fragile-looking galaxies of the outer halo appear to have complex star-formation histories (Mould and Aaronson 1983; see Gallagher and Wyse 1994 for a review), may contribute significantly to the stellar population of the outer halo (Kunkel 1979; Lynden-Bell 1982; Ibata et al. 1994; see a review by Mateo 1996), and may shed fundamental insights on the nature of dark matter in galaxies. My principal goal here is to focus on the latter topic and to provide an update on the kinematic studies of dSph galaxies. I'll restrict myself to studies of resolved dSph systems, which at present means only galaxies in the halo of our Galaxy and perhaps just out to the dwarf companions of M 31.

## 2. Kinematics of Dwarf Spheroidal Galaxies

I will start this summary where an earlier review (Mateo 1994) left off. Please see that paper for a summary of the observational data on dSph galaxies through about 1993 (see also Gallagher and Wyse 1994). The basic nature of kinematic studies of these galaxies has begun to change qualitatively since my last review. Now, multi-object and near-IR spectroscopy has made more of an impact, and serious efforts are underway to extend observations to the very outer limits of individual galaxies and to ever more distant galaxies using new 8-10m class telescopes. Because it is often useful to have the kinematic and structural data in one place, I provide these in Table 1 which is taken from Table 1 of Mateo (1994).

Table 1. Properties of Local Group dSph Galaxies

| Name | $D$ kpc | $R_{GC}$ kpc | $M_V$ mag | $R_c$ pc | $\Sigma_{0,V}$ mag arcsec$^{-2}$ | $I_0$ $L_\odot$ pc$^{-3}$ |
|---|---|---|---|---|---|---|
| Draco | 76 | 76 | −8.7 | 190 | 25.2 | 0.016 |
| Carina | 87 | 89 | −8.9 | 210 | 25.2 | 0.011 |
| Ursa Minor | 63 | 66 | −8.9 | 290 | 25.1 | 0.009 |
| Sextans | 88 | 91 | −10.0 | 380 | 25.5 | 0.004 |
| And III | 690 | 59 | −10.2 | 250 | 24.5 | 0.011 |
| Leo II | 220 | 220 | −10.2 | 220 | 23.8 | 0.037 |
| LGS 3 | 810 | 170 | −10.4 | 190 | 24.8 | 0.011 |
| Sculptor | 78 | 78 | −10.7 | 200 | 24.1 | 0.023 |
| And I | 690 | 39 | −11.7 | 315 | 24.4 | 0.009 |
| And II | 690 | 123 | −11.7 | 330 | 24.5 | 0.008 |
| Leo I | 230 | 230 | −11.7 | 150 | 22.3 | 0.13 |
| Sagittarius | 25 | 16 | −13.0 | 550 | 25.3 | 0.001 |
| Fornax | 131 | 133 | −13.7 | 640 | 23.2 | 0.020 |
| NGC 147 | 690 | 90 | −15.1 | 230 | 21.6 | 0.18 |
| NGC 185 | 690 | 86 | −15.3 | 200 | 20.9 | 0.37 |
| NGC 205 | 690 | 8 | −16.3 | 170 | 19.9 | 1.2 |

$D$ = heliocentric distance.
$R_{GC}$ = Galactocentric distance or projected distance for M31 satellites.
$M_V$ = absolute visual magnitude.
$R_c$ = the approximate King core radius.
$\Sigma_{0,V}$ = central V surface brightness.
$I_0$ = central luminosity density.

I've also included results for systems that have either been discovered (Sgr; Ibata et al. 1994; Mateo et al. 1995; Ibata et al. 1997) or first studied kinematically in the optical (LGS 3; Lo et al. 1993; Lee 1995) since that earlier review. Irwin and Hatzidimitriou (1995) provide a recent compilation of dSph structural parameters; their results are consistent with the data listed in Table 1. Table 2 summarizes the kinematic results from a number of relatively recent studies of resolved dSph galaxies; earlier references can be found in Mateo (1994).

Some of the highlights of these most recent kinematic studies for individual dSph galaxies are listed below:

**Fornax** – Mateo and Olszewski (1997, in preparation) have obtained precise velocities of giants located out to and even somewhat beyond the formal tidal radius of Fornax. These data demonstrate that (a) Fornax is possibly losing some stars to the surrounding halo field, and (b) the velocity dispersion profile of the galaxy is remarkably flat, inconsistent with the profile expected for a King

TABLE 2. RECENT KINEMATIC STUDIES OF DSPH GALAXIES

| Name | $N_*$ | $N_{obs}$ | $\sigma_0$ km/s | $M/L_V$ | Reference |
|---|---|---|---|---|---|
| Carina | 17 | 0 | $6.8 \pm 1.6$ | $39 \pm 23$ | see M94 |
| Draco | 91 | 167 | $8.5 \pm 0.7$ | $57 \pm 9$ | AOP95 |
| | 17 | 17 | $10.5 \pm 2.0$ | $166 \pm 100$ | H96 |
| Fornax | 37 | 45 | $9.9 \pm 1.7$ | $12 \pm 5$ | see M94 |
| | 215 | 250 | $9.6 \pm 1, 8$ | $11 \pm 5$ | in preparation |
| Leo I | 34 | 40 | $9.0 \pm 1.2$ | $8 \pm 3$ | in preparation |
| Leo II | 31 | 37 | $6.7 \pm 1.1$ | $12 \pm 3$ | V95 |
| LGS 3 | 4 | 4 | $7.0 \pm 4.0$ | $20 \pm 15$ | in preparation |
| Sagittarius | $\sim 300$ | $\sim 450$ | $11.4 \pm 0.7$ | $\sim 100$ | I97 |
| Sculptor | 32 | 32 | $7.0 \pm 1.2$ | $9 \pm 4$ | see M94 |
| | 23 | 23 | $6.2 \pm 1.1$ | $9 \pm 6$ | QDP95 |
| Sextans | 33 | 70 | $6.2 \pm 0.8$ | $18 \pm 10$ | S93 |
| | 21 | 30 | $7.0 \pm 1.2$ | $124 \pm 70$ | H94a |
| Ursa Minor | 94 | 206 | $8.8 \pm 0.8$ | $55 \pm 10$ | AOP95 |
| | 35 | 44 | $6.7 \pm 1.0$ | $59 \pm 30$ | H94b |

$N_*$ = number of different stars observed.
$N_{obs}$ = number of total observations.
$\sigma_0$ = central velocity dispersion.
$M/L_V$ = central V-band mass-to-light ratio in solar units.
Abbreviations used here are included with the formal references.

model that best fits the surface-brightness profile of the galaxy (see Figure 1). These results are based on observations of 215 Fornax members.

**Sculptor** – Queloz et al. (1995) published a study of 23 K giants in this southern dSph based on Echelle spectra at ESO. They reobserved many of the stars studied by Armandroff and Da Costa (1986), and found two of these to be significant velocity variables. With the probable binaries removed, the two datasets agreed well. Da Costa and Armandroff (private communication) see no significant change in the velocity dispersion at two radial positions in Sculptor.

**Ursa Minor** – Two groups have published excellent new kinematic results for both this galaxy and Draco. Olszewski et al. (1995, 1996) and Armandroff et al. (1995) have obtained the largest samples of stars yet published for an dSph galaxies; for UMi, 206 observations were obtained of 94 member stars using a variety of instruments and telescopes. Within their datasets, no significant systematic errors were observed. However, these authors do find differences with the results of Hargreaves et al. (1994b), but only at the 1-2$\sigma$ level in the velocity dispersion and the rotation. Both studies find significant evidence for rotation in UMi, but oddly, more nearly along the *minor* axis. The rotation amplitude is much less than the central velocity dispersion, with $v_{rot}/\sigma_0 \sim 0.3$.

The study by Olszewski et al. (1995) is particularly noteworthy because it reports eight years of high-precision velocity measurements of UMi and Dra stars. Velocity variables are certainly present; in all, four good candidates are identified in UMi as probable binaries. But the long-term effects of atmospheric velocity variability appears to be negligible for *bona fide* K giants in UMi.

**Draco** – Olszewski et al. (1996) identify two velocity variables that may be binaries. The sample size in Draco, as for UMi, was greatly increased from earlier work to 167 observations of 91 member stars. Unlike UMi, there is no apparent rotation seen in the Draco kinematic data. Hargreaves, et al. (1996b) have also recently studied Draco, reaching statistically similar results.

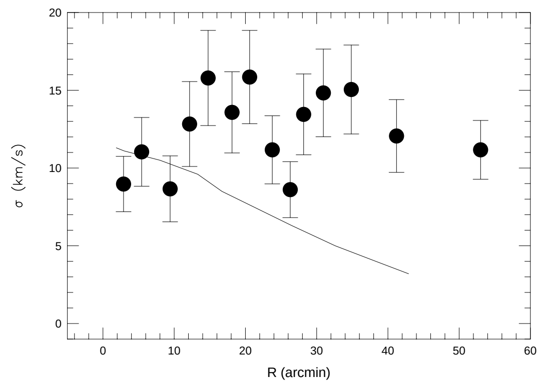


**Figure 1.** The velocity dispersion profile of Fornax. Each bin is based on measurements of 15 galaxy members, except for the outer bin which contains 20 stars.

**Leo II** – Vogt et al. (1995) observed Leo II using the HIRES spectrograph on the Keck 10m telescope and obtained precise velocities of 31 red giants, along with repeat measurements to assess the velocity precision. Because it is located in the outer halo, tidal effects should not affect the kinematics of Leo II, and it was chosen as a test case to distinguish between a dark-matter or tidal origin for the central velocity dispersion. In the end, the derived M/L was neither unusually high, nor low, but rather 'just right'; see section 4 and Figure 2.

**Leo I** – The same group that studied Leo II obtained Keck data for 34 red giants in Leo I; again, the velocity precision is high and was explicitly checked with repeat measurements of Leo I giants. We confirm the large systemic velocity of Leo I (the implications of which are described by Zaritsky et al. 1989) and derived the dispersion listed in Table 2. As for Leo II, Leo I is sufficiently far out in the halo that tidal effects cannot plausibly have affected its internal kinematics. However, Leo I's higher luminosity means that its central velocity dispersion was not expected to be very small even with no dark matter.

**Sagittarius** – Discovered from its kinematic signature within a survey of the Galactic Bulge (Ibata et al. 1994), Sgr provides a unique test case of how a small

galaxy dissolves into the halo of its larger parent. Because of this, the analysis of Sgr is also qualitatively different from that of all the other dwarfs. In particular, one cannot expect to use equilibrium models to properly represent the velocities of stars in Sgr, nor can one ignore the very large spatial extent of the galaxy (Mateo et al. 1996; Alard 1996; Fahlman et al. 1996) and the purely geometric effects on the systemic velocities due to this large angular extent. The results listed in Table 2 – taken from Ibata et al. 1997 – must technically be qualified by the locations at which the measurements were made. However, these authors find relatively little change in the dispersion as a function of distance along the major axis of Sgr along about 10° of its major axis. As this and previous studies have clearly demonstrated (Allen and Richstone 1988; Moore and Davis 1994; Piatek and Pryor 1995; Oh et al. 1995; Johnston et al. 1995; Velazquez and White 1995), the very large extent of Sgr means that detailed models of the interaction of this dwarf with the Galaxy *must* be used to interpret the kinematic measurements.

**Sextans** – Hargreaves et al. (1994a) broadly confirm the observational results of Suntzeff et al. (1993), but because these authors used different structural parameters and the stellar samples are small, the resulting M/L ratios differ by an apparently large amount (however, note that the errors are also large). Hargreaves et al. (1994a) find no evidence for significant rotation in Sextans.

**LGS 3** – K. Cook and C. Stubbs obtained Keck spectra of four bright giants in this dwarf located near M31/M33 which E. Olszewski and I reduced to obtain the velocity dispersion listed in Table 2. Because the sample is so small (four stars) and the velocity precision is modest, we can only conclude that (a) the stellar velocity dispersion is not radically different from that of the meager amount of H I gas in LGS 3 (Lo et al. 1993), and (b) we are at the dawn of an exciting era when 8-10m class telescopes will allow us to study stellar kinematics of dwarfs up to 1 Mpc distant!

## 3. Can We Trust These Results?

The closest dSph systems are about 70 kpc away and are composed of principally old (age $\gtrsim$ 1 Gyr) stars. The central velocity dispersions of these galaxies are expected to be only about 1-3 km/s *if* they contain no dark matter, are unaffected by tidal effects, and if normal Newtonian gravity applies to these very loose, low-surface brightness systems. This all means that we are forced to try to measure precise ($\epsilon_{obs} \lesssim 2$ km/s) velocities of *many* stars fainter than V $\sim$ 17.5, and sometimes in the presence of significant field-star contamination.

Because of these difficulties and because the implications of large central velocity dispersions in dSph galaxies are potentially far-reaching, there has historically – and rightfully – been concern about the reliability of these results. Aaronson's first paper helped set this sceptical tone: he based his estimate of the velocity dispersion of Draco (Aaronson 1983) on measurements of three stars – upgraded to four in a note added in proof!

It should be clear from Table 2 that sample sizes are now no longer a serious

concern in kinematic studies of dSph systems. The worst case (for a Galactic dwarf) is Carina. Larger samples remain important, however, to study the radial velocity dispersion profiles in dwarfs, and to constrain the anisotropy of the velocity distribution of stars in these galaxies.

A second concern has been the influence of binary stars. An early review by Aaronson and Olszewski (1985) described simulations that suggested that binaries are unlikely to inflate the true dispersion to the large observed values in objects such as Draco and Ursa Minor. This result was consistent with the meager direct information on the frequency of binaries in the period range relevant for red giants in dSph galaxies (e.g. Olszewski et al. 1995). More recently, Olszewski et al. (1995, 1996) and Hargreaves et al. (1996a) completed comprehensive simulations of the effects of binaries in dwarf galaxies. Both studies compared the observed vs. true dispersion for samples with and without binaries over large period ranges. Both concluded that the observed binary fractions and a reasonable period distribution cannot account for the dispersions measured in any dSph galaxy. The dispersions have *not* been inflated by orbital motions in undetected binary systems.

Another possible systematic source of bias in the dispersions is atmospheric motions in luminous giants. This so-called 'jitter' is not severe in first-ascent giants in older systems such as dSph galaxies, and it has long been appreciated that the fainter giants are less susceptible to these velocity excursions (Pryor et al. 1988). In practice, most observers have tried hard to obtain data only of the red giants as far below the red giant branch tip as possible. Stars above this luminosity, such as asymptotic giant branch (AGB) C stars, are less reliable, but they remain useful as the most luminous stars in these galaxies, and thus the easiest to observe in the most distant systems. Olszewski et al. (1995) show empirically that the long-term effects of atmospheric motions in dSph giants are negligible.

This summary should make it clear that modern estimates of the velocity dispersions in dSph galaxies *are* generally reliable at the 1-2 km/s precision level. There are two immediate conclusions to draw from this. First, *no* dSph galaxy with adequate observations (see Table 2) has a central velocity dispersion smaller than 6 km/s. Second, the current measurements cleanly rule out velocity dispersions as low as one would expect by merely scaling globular cluster kinematical results by the structural parameters of dSph galaxies (Richstone and Tremaine 1988). There is a fundamental phenomenon reflected in the kinematics of dSph galaxies that we must understand.

## 4. The Origin of dSph Dispersions

This of course begs the question: What is the nature of this fundamental kinematic difference between dwarfs and globulars – dark matter content, tides, anisotropy, the nature of gravity? Or something else? I wish I could answer this, and the frustration with each of these explanations at different times causes me to personally waver on 6-month timescales. Let's consider the possibilities in order of increasing speculativeness (by today's reckoning):

*Dark Matter* – The ‘standard’ physical interpretation for the large dispersions in dSph galaxies is that they contain large quantities of dark matter (DM). The recent observations in Fornax, Sagittarius and to a lesser extent, Ursa Minor, Draco and Sculptor, suggest that if DM is the culprit, it is distributed in a more extended manner than the visible stars. Ibata et al. (1997) in particular argue that the DM in Sagittarius must be particularly extensive to have stabilized that galaxy for many close passages with the Milky Way. Thus, DM halos are large. Pryor and Kormendy (1990) noted that the inferred DM central densities are amazingly high, perhaps as large as 1 $M_\odot/pc^3$ in systems with luminous matter densities of only 1-5% of this value.

Mateo et al. (1993) pointed out that all dSph systems had inferred DM halos of remarkably similar mass, about 1-5 $\times 10^7 M_\odot$. Figure 2 illustrates this feature along with new data from additional systems. The dashed line represents the equation $M_{tot,0} = 5.0 L_{tot} + 2.5 \times 10^7 M_\odot$, where $M_{tot}$ is the ‘total’ mass, $L_{tot}$ is the total luminosity, and the factor ‘5.0’ is taken as the standard V-band M/L ratio of the visible stars in the galaxy – all quantities are in solar units. In all cases (except Sagittarius), the masses assume that mass follows light and isotropic orbits (Richstone and Tremaine 1988), so they represent the total masses of the galaxies as derived from their central kinematic/structural properties. Nonetheless, the in Figure 2 correlation is striking, perhaps telling us that DM halos in dSph systems are somehow intimately related and, because of the deviant location of Sagittarius, that severe tidal effects do ultimately affect the inferred M/L ratios (see also Bellazzini et al. 1996). Do such minimum-sized ‘chunks’ of DM that contribute to the halos of larger galaxies, groups and clusters?

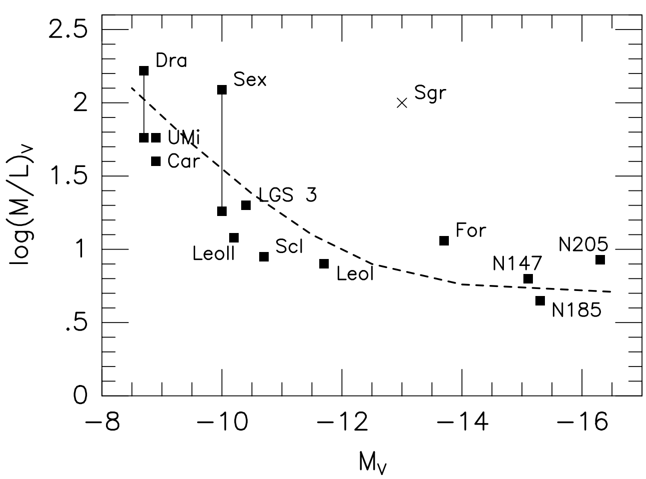


**Figure 2.** The correlation between $M/L_V$ and $M_V$ for Local Group dSph galaxies with good kinematic data. The dashed line is equivalent to a model where each galaxy has a dark halo mass of $2.5 \times 10^7 M_\odot$ plus a luminous component with $M/L_V = 5.0$. Sagittarius is noted with a cross. The data for the Andromeda dwarfs (apart from LGS 3) come from the references in Mateo 1994.

It is interesting to note that dSph galaxies provide one of the only constraints on what DM isn't. As first noted by Faber and Lin (1983) and updated by Gerhard and Spergel (1992), phase space restrictions demand that if neutrinos provide the DM in these galaxies, the neutrino mass must be much larger than current experimental upper limits.

*Galactic Tides* – Hodge and Michie (1969) noted that the structural parameters of Ursa Minor indicate that it may be in the terminal phases of complete disruption due to severe tidal interaction with the Milky Way. That some dSph galaxies are affected by Galactic tides is indisputable. Sagittarius is a clear example, but Carina (Kuhn et al. 1996), and possibly Sextans (Gould et al. 1992) have had member stars detected far from the main bodies of the galaxies. Radial surface density profiles of dSph systems (Irwin and Hatzidimitriou 1995) suggest that many of these galaxies seem to 'melt' into the surrounding halo.

Nonetheless, for many people, kinematic measurements 'confirmed' suspicions that DM stabilizes these galaxies against disruption. Recent models (particularly Piatek and Pryor 1995 and Oh et al. 1995) argue that tides could not possibly inflate the *central* dispersions to the observed values without also observing strong streaming motions (that would be interpreted as rotation). Pryor (1996) offers a recent review of these studies and their conclusions.

Another class of models directly challenges the conclusion that dSph systems are DM dominated. Kuhn and Miller (1989) and Kroupa (1996) argue that resonances between the internal oscillation periods of dSph galaxies induced by tides and their orbital periods could make systems with large central dispersions persist for extended periods. It would be of great interest to widely confirm and expand on these models to understand if the resulting dwarfs are indeed sufficiently long-lived to be seen as (mostly) non-rotating dwarfs with large central velocity dispersions. It is hard to understand how tides account for Figure 2, though small-number statistics could conceivably still be important.

*Modified Gravity* – This is clearly the currently least popular option at present. Milgrom has argued that MOND (MOdified Newtonian Gravity) offers an alternative explanation of the observed kinematical results for dSph galaxies if the observational uncertainties are realistically accounted for (Milgrom 1995; see Gerhard 1994 for a different view). Even one undisputed failure of MOND would disqualify it, unless we also wish to consider a non-universal modified gravity law! But disagreements remain whether such failures are observed, while some impressive successes have been noted among large high- and low-surface brightness galaxies (McGaugh, private communication; Mannheim 1997). My point here is merely that dSph galaxies are not obviously inconsistent with Milgrom's version of MOND, a concept originally designed to explain rotation curves of galaxies thousands of times more luminous than dSph systems.

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